TECHNICAL REPORT

Contract Title:	Infrared Algorithm Development for Ocean Observations with EOS/MODIS
Contract:	NAS5-31361
Type of Report:	Semi-Annual
Time Period:	January- June 2001
Principal Investigator:	Otis B. Brown RSMAS/MPO University of Miami 4600 Rickenbacker Causeway Miami, Florida 33149-1098

INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

Abstract

Efforts continue under this contract to develop and validate algorithms for the computation of sea surface temperature (SST) from MODIS infrared measurements. These include radiative transfer modeling, comparison of *in situ* and satellite observations, development and evaluation of processing and networking methodologies for algorithm computation and data access, evaluation of surface validation approaches for IR radiances, and participation in MODIS (project) related activities. Activities in this contract period have focused on field campaigns, analysis of field data, analysis of MODIS SST retrievals, preparation of publications and presentations and, with external funding, the organization of and participation in the *International Infrared Radiometer Intercomparison*, held at the University of Miami – Rosenstiel School in May 2001.

A. NEAR TERM OBJECTIVES

MODIS Infrared Algorithm Development And Maintenance

A.1. Algorithmic development efforts based on experimental match-up databases and radiative transfer models and inter-satellite comparisons

A.2. Interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST activities.

A.3 Maintain and develop at-sea instrumentation for MODIS SST validation.

A.4 *In situ* validation cruises for the MODIS IR bands.

A.5 Development and population of the M-AERI Data Base, the Oceanographic and Atmospheric Archive and Retrieval System (OAARS).

MODIS SST – Scientific Research

A.6 Study thermal structure of ocean-atmosphere interface.

A.7 Development of optimal skin-SST validation strategy.

Overarching Contract Activities

A.8 Provide investigator and staff support for the preceding items.

B. OVERVIEW OF CURRENT PROGRESS

January – June 2001

Activities during the past six months have continued on the previously initiated tasks. There have been specific efforts in the areas of: (a) cruises to acquire MODIS infrared validation data and (b) development of an interim SST retrieval algorithm based on match-up with AVHRR Pathfinder data (Evans). In addition, previously initiated activities, such as team related activities, continue, as have episodic efforts associated with MODIS anomaly characterization and response.

Special foci during this six-month period have been:

1) Development of an interim SST retrieval algorithm based on match-up with AVHRR Pathfinder data for the derivation of the atmospheric correction algorithm for SST retrieval. (R. Evans)

2) Continuation of the analysis of measurements from M-AERI research cruises (Table 1).

3) Continuation of routine data collection on the *Explorer of the Seas.*

4) Preparation and participation in the cruise of the *USCGC Polar Sea* from Australia to Seattle (March to May 2001).

5) Preparation and participation in the cruises of the NOAA ship *Ronald H Brown* in the Tropical Pacific Ocean, as part of the Gasex'01 and ACE-ASIA Campaigns (January – May 2001).

6) Maintenance of the at-sea hardware.

7) Continue development of a purpose-built computer database for validation cruise data and associated satellite measurements.

8) Implementation of various SST data assimilation approaches.

9) In collaboration with Dr B. Ward of the CIMAS, and Dr. M. Donelan of the University of Miami a study of the thermal skin layer with his micro-profiler and the M-AERI, in the University of Miami – Rosenstiel School ASIST facility, has begun (with ONR funding).

10) Plan and conduct the *2nd International Infrared Intercomparison* at the University of Miami – Rosenstiel School (with funding from NOAA, ESA and EUMETSAT).

B.1. Algorithmic development efforts based on experimental match-up databases and radiative transfer models and inter-satellite comparisons.

As a result of the intensive efforts at the University of Miami – Rosenstiel School and in the MCST to develop corrections for the instrumental effects on the SST bands of MODIS, it has become possible to apply the atmospheric correction algorithms to on-orbit data to derive SST fields. This has been done on a number of test cases, using the algorithms derived by numerical simulations of the MODIS brightness temperatures, and while the results are reasonable, they show some disconcerting attributes when compared to AVHRR Pathfinder fields for the same periods. Comparisons between the MODIS nighttime SSTs derived from the thermal infrared bands (31 and 32) and the mid-ir bands (20,22,23) show systematic, non-physical trends, with discrepancies reaching a degree in extreme cases (Figure 1). There are several possible causes for these discrepancies:

1. The MODIS does not behave in the way we believe it should be behaving, either as a result of incomplete pre-launch characterization, a change in the MODIS properties between pre-launch characterization and on-orbit performance, or a consequence of the *ad-hoc* corrections applied to compensate for the instrumental artifacts (or a combination of these).
2. Imperfections in the radiative transfer model used to simulate the MODIS brightness temperature measurements. A candidate for this is the anomalous water vapor continuum absorption.
3. Inaccuracies in the atmospheric properties used to drive the radiative transfer model. We are using a large set of atmospheric profiles over the oceans derived from the 4-D data assimilation model of the ECMWF. It is possible that these profiles are perfectly consistent with the ECMWF model but still contain systematic uncertainties with respect to the real atmospheric properties.
4. A combination of the above.

Efforts are underway to investigate these potential sources of error and to refine the infrared atmospheric correction algorithms derived from the radiative transfer simulations.

To provide a workable atmospheric correction algorithm for MODIS infrared observations, an regression analysis between MODIS brightness temperatures and AVHRR Pathfinder SST fields was performed to provide coefficients for the MODIS SST. This approach ties the accuracy of the MODIS SSTs to the Pathfinder SSTs, the accuracies of which have been demonstrated at the 0.3K level by comparisons with M-AERI data (see Kearns *et al*., 2000), rather than to forward radiative transfer models. This approach is seen as an interim measure until confidence in a more rigorously derived correction algorithms can be established.

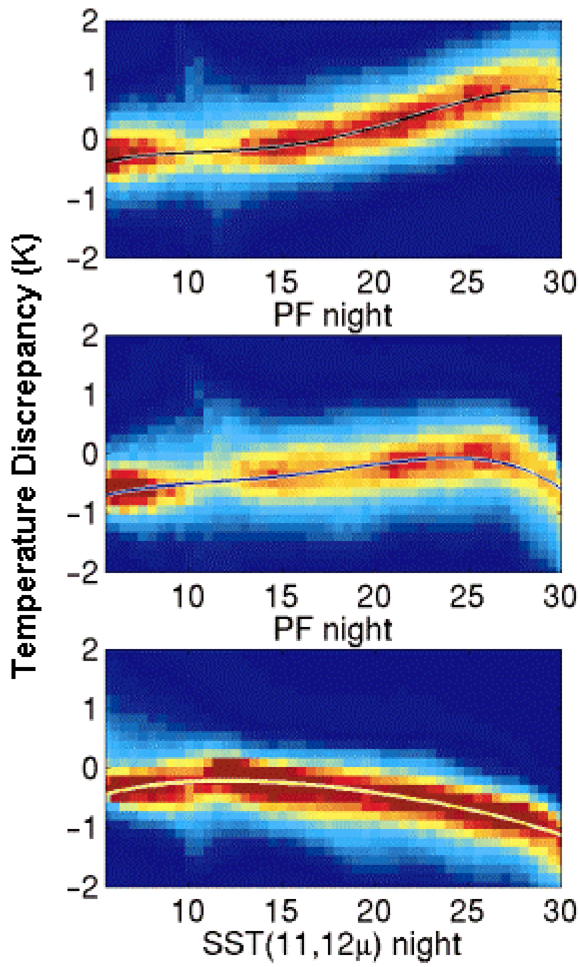

Figure 1. Distributions of temperature discrepancies between MODIS-derived SST fields and AVHRR Pathfinder SST fields. Warm-pixel composites of global data from August 30 to September 6, 2000 were used. Nighttime only data are shown here. The top panel shows MODIS SSTs from Bands 31 and 32, minus the Pathfinder SSTs as a function on the Pathfinder SSTs; the center panel shows MODIS SSTs from Bands 20 and 23, minus the Pathfinder SSTs as a function on the Pathfinder SSTs; the bottom panel shows MODIS SSTs from Bands 20 and 23, minus the MODIS SSTs from Bands 31 and 32 as a function on the MODIS SSTs from Bands 31 and 32.

<u>B.2. Interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST activities.</u>

Otis Brown attended the *Oceanology International Americas 2001* conference in Miami, April 3-5 2001, and gave an invited paper entitled "Satellite Earth Remote Sensing: The Earth Observing System and the Next Decade."

Peter Minnett attended the MODIS Science Team Meeting, Columbia MD, January 24-26, and presented "Prospects for Improved Sea-surface temperatures from MODIS – Superior Accuracy and Refined Applications" to the plenary session. He also attended the Aqua Science Working Group and Validation Meetings on February 7 and 8 at Goddard, and the MODIS Cloud Mask Workshop, Madison WI, May 8 and 9, 2001. As a result of the Cloud Mask Workshop, we have been invited to contribute at-sea measurements to a validation database being set up for the ASTER Team (R. Walsh, U. Alabama).

Interaction with Bob Evans (Contract NAS5-31362) and others at RSMAS on a daily basis to discuss the remediation of MODIS instrumental issues; numerous telephone discussion with Wayne Esaias, MODIS Oceans Team Leader on MODIS SST retrievals.

B.3 Maintain and develop at-sea instrumentation for MODIS SST validation.

The cabling problems associated with the MAERI-1installation on the *Explorer of the Seas* were resolved in the early part of the reporting period. These were associated with housekeeping variables and not with the interferometer data.

Following the severe disk crash of the MAERI-2 computer on the cruise of the *USCGC Polar Sea* in November, 2000, the equipment was shipped back to SSEC in Madison for refurbishment and repair. This was completed quickly and although no useful data were taken during the Polar Sea cruise, MAERI-2 was installed on the NOAAS *Ronald H. Brown* in time for the start of the GASEX 2001 and ACE-Asia cruises (see B.5). MAERI-3 was returned to SSEC to refurbishment and realignment of the optical bench; it has a residual problem that causes the computer to lock-up, and this is proving very hard to diagnose and correct. It does not lead to a severe data loss provided the operator is alert and corrects the problem when it arises.

In collaboration with Dr R.M. Reynolds of the Brookhaven National Laboratory, a Portable Radiation Platform (PRP), comprising a Fast Rotating Shadowband Radiometer and broadband 2π long- and short-wave radiometers, was prepared for installation on the Explorer of the Seas. The purpose of this is to determine the atmospheric aerosol parameters during MODIS overpasses.

B.4 *In situ* validation cruises for the MODIS IR bands.

MAERI-1 is permanently installed on the *Explorer of the Seas*, which undertakes weekly cruises in the eastern Caribbean Sea and Bahaman Islands (Figure 2). The ship returns to Miami each Saturday at which time the data are retrieved and taken to RSMAS. The data return has been very good (Figure 3).

Figure 2. Weekly track of the *Explorer of the Seas*

MAERI-2 was installed on the *NOAAS Ronald H. Brown* at the start of the GASEX 2001 and ACE-Asia cruises. The GASEX cruise was form Miami to Honolulu, and ACE-Asia from Honolulu to Yokohama. The MAERI remained on board for the section from Japan to Alaska. The cruise track is shown in Figure 4. The MAERI, and ancillary instruments worked very well throughout the cruises, which encompassed a wide range of environmental conditions for MODIS validation.

MAERI-3 was embarked on the *USCGC Polar Sea* in Adelaide for the return section across the Pacific Ocean. The track is shown in Figure 5. Again, the instruments functioned well, although the computer continues to lock-up intermittently, and again a wide range of environmental conditions were experienced during the cruise.

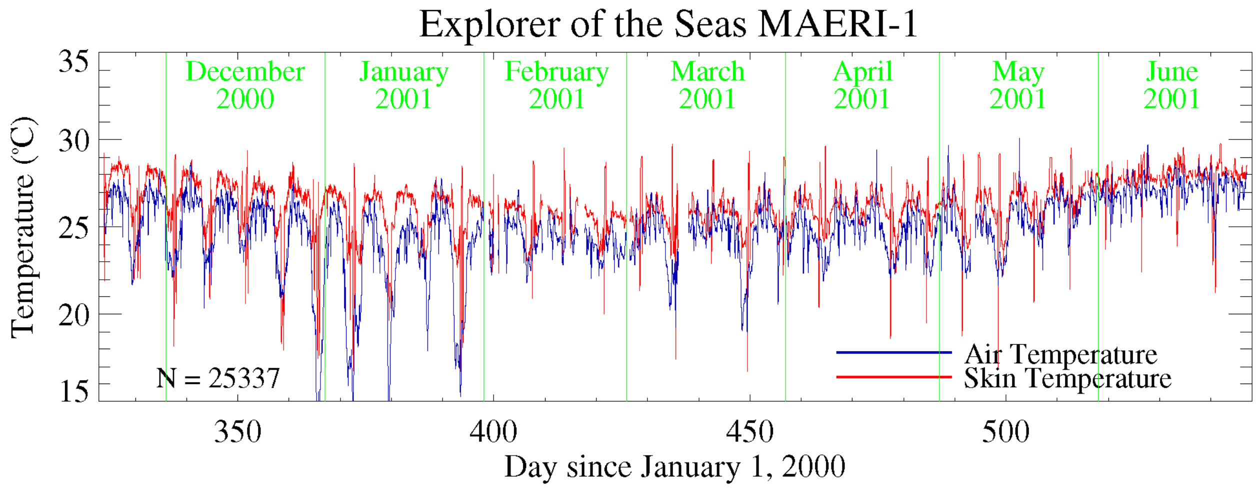

Figure 3. Skin SST and near-surface air temperatures measured by MAERI-1 on the *Explorer of the Seas*, since installation in November 2000.

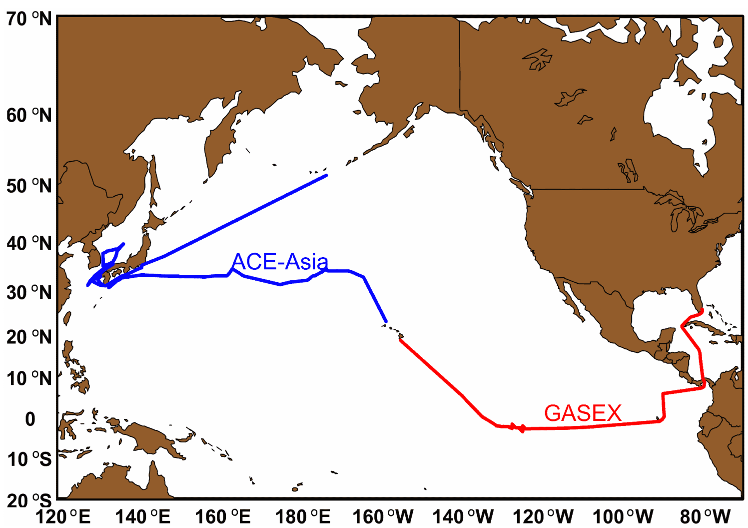

Figure 4. Track of the *NOAAS Ronald H. Brown* during the GASEX and ACE-Asia cruises. The GASEX cruise began in Miami on January 28, and ended in Honolulu on March 3. ACE-Asia began in Honolulu on March 15 and ended in Dutch Harbor, May 3.

B.5 Development and population of the M-AERI Data Base, the Oceanographic and Atmospheric Archive and Retrieval System (OAARS).

The OAARS database is located at http://www.rsmas.miami.edu/ir/maeri-db and is constantly being populated with new data sets. The database now contains data for 19 M-AERI cruises with 9 search options available. The most recent addition is the capability to download netCDF files of the full spectrum M-AERI radiance data.

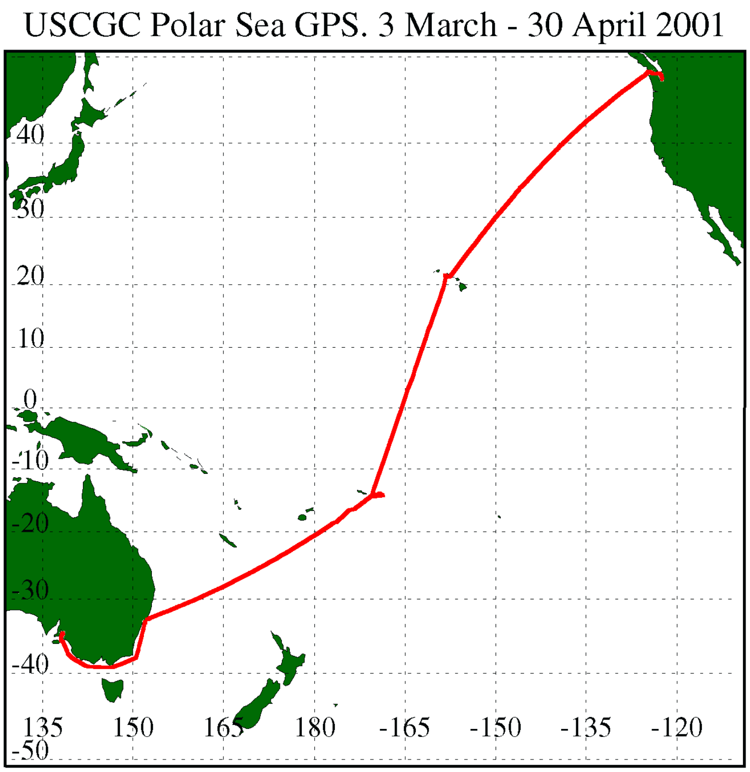

Figure 5. Track of the *USCGC Polar Sea*. The ship left Adelaide, South Australia, on March 3, and arrived in Seattle, WA, on 30 April 2001.

The biggest addition is a section designed entirely for the *Explorer of the Seas* data (just click on the ship icon). This data is stored in monthly data sets, on the same time interval, and at one-minute resolution. The data sets include Navigation, Thermosalinograph, Weather Pak (Bow and Stern), Eppley Radiometers, Optical Rain Gauge, Anemometers (Port and Starboard), Total Sky Imager, and Ceilometer. Data from December 2000 up through April 2001 is currently on the database. The *Explorer* data set has five search options and its own graphic capabilities. M-AERI SST data can always be accessed from both areas of the database.

Table 1 is a listing of the M-AERI projects in the database. Table 2 the data archive for the M-AERI projects, and Table 3 is the data archive for the *Explorer* projects. Figure 1 is a graph of all the past M-AERI projects.

Future work entails adding the Ceilometer and Total Sky Imager data from all of the past *Explorer* projects to the database and adding new monthly *Explorer* data sets and M-AERI project data sets.

Project	Ship	YYYYMMDD	Start Port	End Port	Instrument
CSP1996 Combined Sensor Cruise	NOAA Ship Discoverer	19960314-19960413	Pago-Pago, Am. Samoa	Honolulu, HI	Prototype
HiNz1997 Hawaii-New Zealand Transit	R/VRoger Revelle	19970928-19971014	Honolulu, HI	Lyttleton, NZ	M-AERI 1 and 2
24N1998 OACES 24 N Section	NOAA S Ronald H. Brown	19980108-19980224	Miami, FL	Miami, FL	M-AERI 1
NOW1998 North Water	CCGS Pierre Radisson	19980326-19980728	Quebec City, Canada	Nanisivic, Canada	M-AERI 2
GASEX1998 OACES Gasex	NOAA S Ronald H. Brown	19980502-19980707	Miami, FL	Miami, FL	M-AERI 1
PANAMA1998 Panama Transit	NOAA S Ronald H. Brown	19980712-19980727	Miami, FL	Newport, OR	M-AERI 1
PACS1998 PanAmerican Climate Studies-mooring recovery	R/V Melville	19980908-19980929	San Diego, CA	San Diego, CA	M-AERI 1
SLIP1999 Western Pacific Transect, St. Lawrence Island Polynya	USCGS Polar Sea	19990301-19990511	Adelaide, Austrailia	Seattle, Washington	M-AERI 2
NAURU1999	R/V Mirai	19990608-19990720	Yokohama, Japan	Sikenehama, Japan	M-AERI 1
NOW1999 North Water	CCGS Pierre Radisson	19990824-19991010	Quebec City, Canada	Quebec City, Canada	M-AERI 2
MODIS1999	R/V Melville	19991001-19991020	San Diego, CA	San Diego, CA	M-AERI 1
URANIA1999	NAVE Urania	19991019-19991111	Messina, Sicily	Civitavechhia, Italy	M-AERI 3
EAT1999 Eastern Atlantic Transect	R/V Polarstern	19991215-20000106	Bermerhaven, Germany	Cape Town Africa	M-AERI 3
PSTAR2000 Pacific Transect	USCGC Polar Star	20000304-20000501	Melbourne, Australia	Seattle, WA	M-AERI 2
URANIA2000 Gulf of Lions	R/V Urania	20000325-20000418	Naples, Italy	Naples, Italy	M-AERI 3
AWS2000 Arctic West Summer	USCGC Polar Star	20000727-20000922	Seattle, WA	Seattle, WA	M-AERI 2
GASEX2001 OACES Gasex	NOAA S Ronald H.Brown	20010727-20010308	Miami, FL	Honolulu, HI	M-AERI 3
PSEA2001 Pacific Transect	USCGS Polar Sea	20010314-20010506	Adelaide, Austrailia	Seattle, WA	M-AERI 2
ACE2001 Asia East	NOAA S Ronald H. Brown	20010314-20010503	Honolulu, HI	Dutch Harbor, AK	M-AERI 3

Table 1 M-AERI Projects in the Database

Cruise	**CSP**	**HiNz**	**24N**	**NOW**	**GASEX**	**PANAMA**	**PACS**	**SLIP**
Year	**1996**	**1997**	**1998**	**1998**	**1998**	**1998**	**1998**	**1999**
DataName								
MaeriSst	1429	2294	3090	16356	6773	2062	2904	6507
MaeriRet	19260							
MaeriQc		53	199	554327	138	42	85	139620
Wpac	Not Used	28915	65458	144008			Not Used	98316
ShipMet	84690		107483	Not Used	77505			Not Used
Tsg	78039	21600	107483	62273	83962	39955		
Rsonde	81594	1086	9593	208745	314969		207887	147535
HardHat	44085	Not Used		37441	66755	Not Used	2582	12673
ShipNav	246761		107483	58456				
Irt	51941	88651			Not Used			
ShipRad				5591				
Prp	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used	
Ctd			575407					
Xbt								
Adcp			53519					
Org								

Cruise	**NAURU**	**NOW**	**MODIS**	**URANIA**	**EAT**	**PSTAR**	**URANIA**	**AWS**
Year	**1999**	**1999**	**1999**	**1999**	**1999**	**2000**	**2000**	**2000**
DataName								
MaeriSst	2250	4874	2265	1658	2138	7102	2104	5705
MaeriRet								
MaeriQc	34803	57887	11501	16386	32360	45816	18119	105302
Wpac				56855	32077	79626	30929	72974
ShipMet	25245		29195	12060	19455		31610	
Tsg			29197	12060	21609	218213	31610	
Rsonde			Not Used		10346	49020	115303	29858
HardHat			37003	53584	Not Used	Not Used	1155	7100
ShipNav	25245		29197	12062	17062	22202	31610	65653
Irt	Not Used		Not Used	Not Used	Not Used	Not Used	Not Used	
ShipRad	10602		29197				31610	
Prp	22853			Not Used			Not Used	
Ctd				186224				
Xbt				7978				
Adcp								
Org					12287			

Cruise	**GASEX**	**PSEA**	**ACE**
Year	**2001**	**2001**	**2001**
DataName			
MaeriSst	3046	2757	4907
MaeriRet			
MaeriQc	134682	43109	229909
Wpak		56214	
ShipMet	40925		49976
Tsg	40925	27561	19935
Rsonde	23142	5235	40429
HardHat			20624
ShipNav	40925	17313	48825
Irt			
ShipRad			
Prp	20561		40970
Ctd			
Xbt			
Adcp			
Org			
RadSst	1204		1992

Table 2. Data Archive of M-AERI cruises

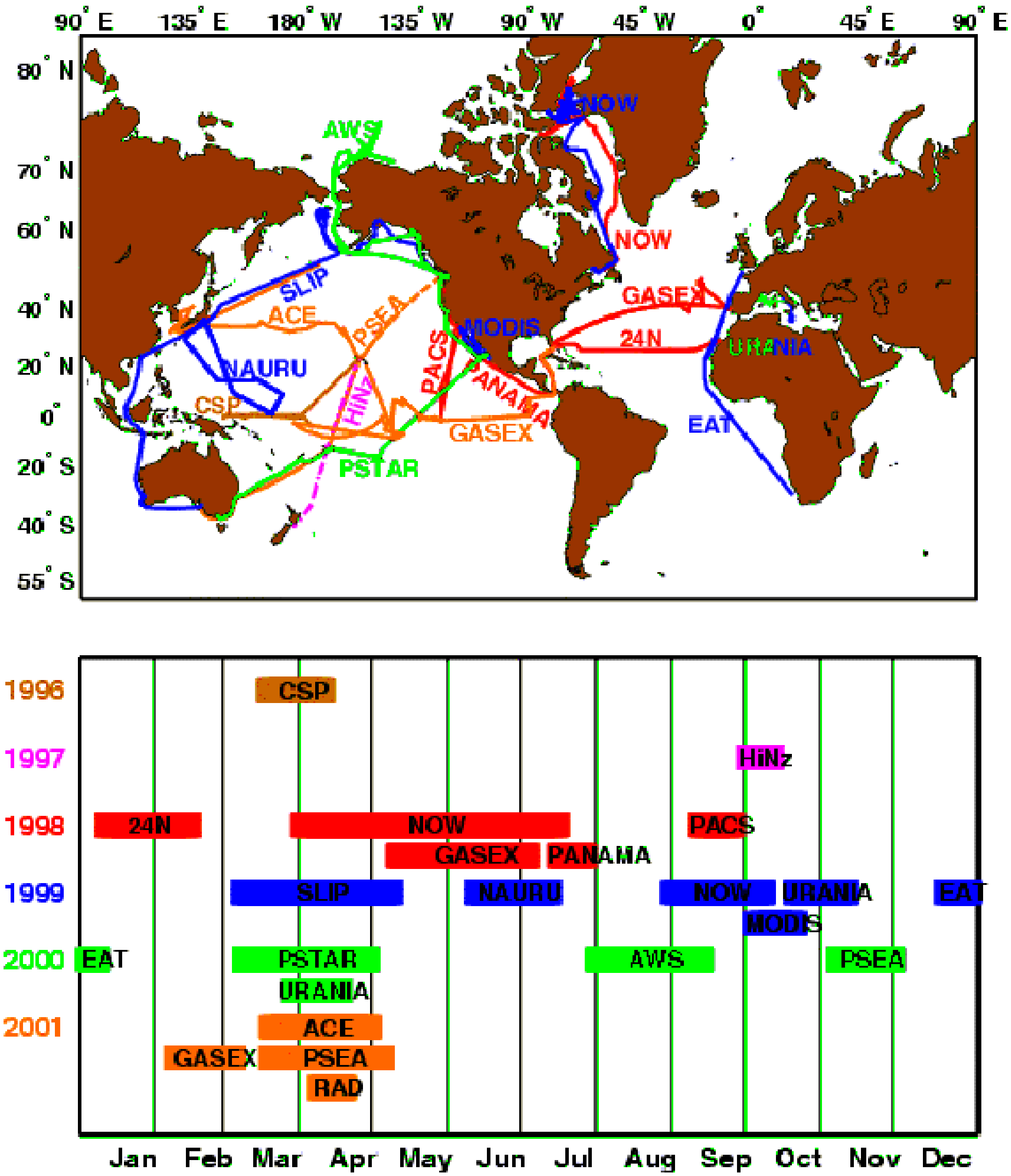

Figure 6. Past M-AERI Observations

Cruise	EXP11	EXP12	EXP01	EXP02	EXP03	EXP04
Year	**2000**	**2000**	**2001**	**2001**	**2001**	**2001**
DataName						
MaeriSst	1582	2735	2465	1993	25963	2861
ExpNav		42357	43091	39814	43947	43068
ExpEppley		42357	43091	39814	43947	43068
ExpAnnePort		42357	43091	39814	43947	43068
ExpAnneStar				39814	43947	43068
ExpOrg		42357	43091	39814	43947	43068
ExpWpakBow				39814	43947	43068
ExpWpakFwd		42357	43091	39814		
ExpWpakStn				39814	43947	43068
ExpPlankton						
ExpTsg						43068
ExpTsi						
ExpCeil						

Table 3. Data archive for the *Explorer of the Seas*

MODIS SST – Scientific Research

B.6 Study thermal structure of ocean-atmosphere interface.

The air-sea temperature difference is a critical parameter in the coupling of the energetics of the ocean and atmosphere. It is usually measured by two thermometers mounted on a ship or a buoy, one in the air and one in the ocean. The air-sea temperature difference is generally less than a couple of degrees and so uncertainties in the calibrations of the thermometers can lead to significant errors in the measurement of the difference. The M-AERI can measure both the skin SST and a near-surface air temperature, and these are both calibrated by reference to NIST-traceable black-body targets. The M-AERI measurement of air-sea temperature difference is therefore a much better representation of the true value. Analysis of M-AERI air-sea temperature differences taken during several research cruises show significant discrepancies compared to measurements made using conventional instrumentation. The M-AERI data are in all cases much less variable over the course of the day and 'better behaved.' Figure7 shows examples taken in the equatorial Pacific during the NAURU99 cruise of the *R/V Mirai*. The conventional data show very large diurnal excursions, with the sign of the temperature difference, and hence the air-sea heat flow, changing sign each afternoon. This feature is absent from the radiometrically-derived difference (M-AERI data). The large diurnal excursions are believed to result from heating of the air-temperature thermometer by the 'heat-island' effect of the ship. This has significant ramifications on our perception of how the ocean and atmosphere interact as this is based entirely on such measurements taken form ships. It also has implication on possible applications of MODIS SST data in terms of estimating air-sea heat fluxes.

The wavelength dependence of the emission depth of thermal infrared radiation measurement by the M-AERI implies that the spectra contain information about the vertical temperature gradients with in the thermal skin layer of the ocean. This has been demonstrated in the laboratory by McKeown *et al.* (McKeown, W., F. Bretherton, H.L. Huang, W.L. Smith, and H.L. Revercomb, Sounding the skin of water: sensing air-water interface temperature gradients with interferometry., *J. Atmos. and Oceanic Tech.*, **12**, 1313-1327., 1995) and the technique is being refined and applied to at-sea M-AERI data from several research cruises by Jennifer Hanafin, a Ph.D. student at RSMAS. Initial results are very promising.

With funding from ONR a study has begun of the thermal skin layer and subsurface temperature structure in the RSMAS ASIST (Air-Sea Interaction Salt Water Tank). ASIST was designed for studies relevant to air-sea interaction including remote sensing, turbulence, gas transfer, wave dynamics, surface chemistry, spray and aerosol generation, and interfacial thermodynamics. The 15 meter long ASIST is equipped with a wind tunnel (0-30 m/s), programmable wavemaker, water temperature control, water current control, turbulence and wave instrumentation. This is in collaboration with Dr B. Ward of the CIMAS, and Dr. M. Donelan of RSMAS.

B.7 Development of optimal skin-SST validation strategy.

The measurements of the open ocean thermal skin effects by the M-AERI over many cruises have shown a consistent dependence on the local wind speed. At winds greater than about 6 m/s the variability of the skin-bulk temperature difference is invariant at the level of ~0.15K, with a slight wind speed dependency. There is relatively little difference between night and daytime conditions. This result is supported by similar measurements using other, well-calibrated radiometers. This means that conventional measurements of bulk SST made by drifting and moored buoys can be used for the validation of satellite-derived SST, provided such data are restricted to appropriate wind speed conditions. For low winds, well-calibrated radiometers or interferometers should be used. These data and results have been written up and will appear in the *Journal of Climate* (Donlon *et al.*, 2001).

During the last week of May, 2001 an international workshop for the comparison and calibration of ship-board infrared radiometers that are being used to validate the skin sea-surface temperatures derived from the measurements of imaging radiometers on earth observation satellites, was held at RSMAS. This included laboratory measurements using the newly developed NIST Transfer Radiometer (TXR), and against NIST-certified black-body calibration targets, and an intercomparison of the radiometers on a short cruise on board the R/V F.G. Walton-Smith in local waters around Miami. This was funded by NOAA, ESA and EUMETSAT.

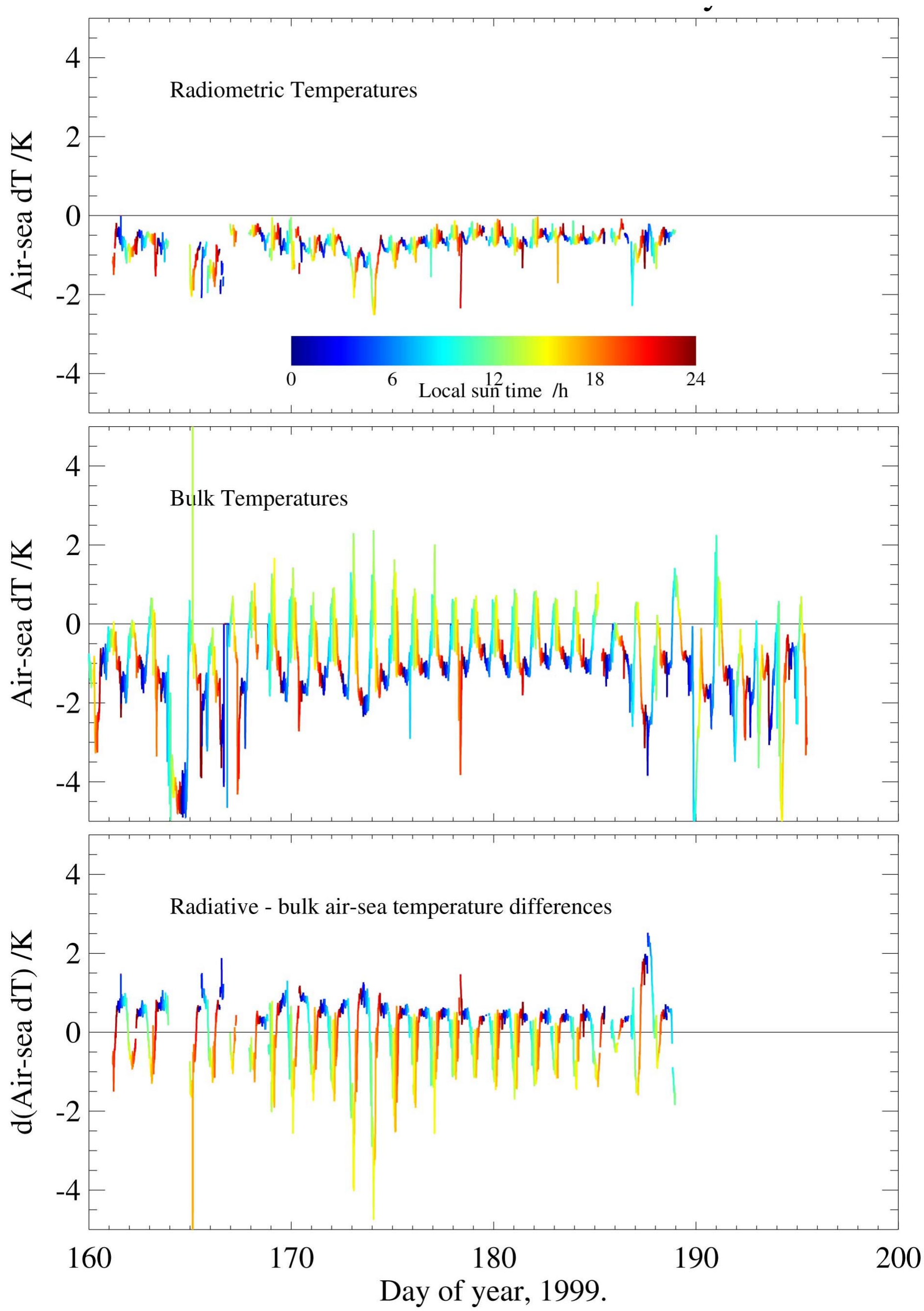

Figure 7. Measurements of Air-sea temperature differences taken by the M-AERI (top panel) and conventional sensors (center panel) on the *R/V Mirai*. The cruise began and ended in Japan. The data shown here were taken on passage from Japan, and close to the Equator; 6 June to 7 July, 1999. Air-sea temperature differences are generally <2K.There are some diurnal fluctuations, especially in clear sky conditions. Radiometric measurements show marked differences to those from conventional sensors.

C. Investigator Support

January	W. Baringer	R. Kolaczynski	K. Maillet
	O. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
February	W. Baringer	R. Kolaczynski	K. Maillet
	O. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick		
March	W. Baringer	R. Kolaczynski	P. Minnett
	O. Brown	R. Kovach	R. Sikorski
	M. Framinan	A. Li	J. Splain
	K. Kilpatrick	K. Maillet	M. Szczodrak
April	W. Baringer	R. Kolaczynski	P. Minnett
	O. Brown	R. Kovach	R. Sikorski
	M. Framinan	A. Li	J. Splain
	K. Kilpatrick	K. Maillet	M. Szczodrak
May	W. Baringer	R. Kolaczynski	K. Maillet
	O. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick		
June	W. Baringer	R. Kolaczynski	K. Maillet
	O. Brown	R. Kovach	J. Splain
	M. Framinan	A. Li	M. Szczodrak
	K. Kilpatrick		

D. Future Activities

D.1 Algorithms

- a. Continue to develop and test algorithms on global retrievals
- b. Evaluation of global data assimilation statistics for SST fields
- c. Participate in research cruises
- d. Analyze data taken at radiometer and validation workshops
- e. Continue radiative transfer modeling
- f. Continue analysis of research cruise data
- g. Continue to study near-surface temperature gradients
- h. Continue planning of post-launch validation campaigns
- i. Validation Plan updates (as needed)
- j. EOS Science Plan updates (as needed)
- k. Define and implement an extended ATM based network test bed
- l. Continued integration of new workstations into algorithm development environment
- m. Continued participation in MODIS Team activities and calibration working group

D.2 Investigator support

Continue appropriate efforts.

D.3 Presentations and publications.

- a. Prepare material for the IGARSS International Symposium in Sydney in July.
- b. Prepare scientific results for publication in the refereed literature.

E. Problems

F. Publications and Presentations

F.1 Refereed publications:

Donlon, C. J., P. J. Minnett, C. Gentemann, T. J Nightingale, I. J. Barton, B. Ward and J. Murray, 2001. Towards improved validation of satellite sea surface skin temperature measurements for climate research. *J. Climate*. Accepted.

A poor validation strategy will compromise the quality of satellite-derived sea-surface temperature (SST) products because confidence limits cannot be quantified. This paper addresses the question of how to provide the best operational strategy to validate satellite-derived skin sea-surface temperature (SST_{skin}) measurements. High quality in situ observations obtained using different state-of-the-art infrared radiometer systems are used to characterize the relationship between the SST_{skin}, the subsurface SST at depth (SST_{depth}) and the surface wind speed. Data are presented for different oceans and seasons. These data indicate that above a wind speed of approximately 6 ms^{-1} the relationship between the SST_{skin} and SST_{depth}, is well characterized for both day and night time conditions by a cool bias of 0.17 ±0.07 rms. K. At lower wind speeds, stratification of the upper ocean layers during the day may complicate the relationship while at night a cooler skin is normally observed. Based on these observations, a long-term global

satellite SST_{skin} validation strategy is proposed. Emphasis is placed on the use of autonomous, ship of opportunity radiometer systems for areas in areas characterized by prevailing low wind speed conditions. For areas characterized by higher wind speed regimes, well calibrated, quality controlled, ship and buoy SST_{depth} observations, corrected for a cool skin bias should also be used. It is foreseen that SST_{depth} data will provide the majority of in situ validation data required for operational satellite SST validation. We test the strategy using SST_{skin} observations from the Along Track Scanning Radiometer, that are shown to be accurate to ~0.2 K in the tropical Pacific Ocean, and using measurements from the Advanced Very High Resolution Radiometer. We note that this strategy provides for robust retrospective calibration and validation of satellite SST data and a means to compare and compile in a meaningful and consistent fashion similar data sets. A better understanding of the spatial and temporal variability of thermal stratification of the upper ocean layers during low wind speed conditions is fundamental to improvements in SST validation and development of multi-sensor satellite SST products.

Hanafin, J. A. and P. J. Minnett, 2001. Profiling temperature in the sea surface skin layer using FTIR measurements. *Gas Transfer at Water Surfaces.* edited by M. A. Donelan, W.M. Drennan, E.S. Saltzmann and R. Wanninkhof. *American Geophysical Union Monograph.* Accepted

Sea surface spectral emissivity and the depth of the thermal skin boundary layer were determined using high spectral resolution measurements of the sea surface and the atmosphere taken in the field measurements by the Marine-Atmosphere Emitted Radiance Interferometer. In order to determine the sea surface emissivity, the effective incidence angle was found by minimizing the variance in the brightness temperature spectrum retrieved from the corrected upwelling radiance spectrum. Certain wavelength regions have different absorption characteristics, allowing the temperature at different levels to be retrieved from different spectral regions. In this way, the temperature gradient of the thermal boundary layer was determined. The depth of the skin layer was then calculated by determining the depth at which the thermometrically measured bulk temperature intersects this gradient. At low wind speeds, the skin layer can be up to 0.2mm deep, getting shallower with increased wind speed and becoming very shallow (0.01-0.07mm) above wind speeds of $8ms^{-1}$. These results are encouraging for application of this method to determine air-sea heat and gas fluxes in the field.

Minnett, P.J., 2001, Satellite Remote Sensing: Sea Surface Temperatures. *Encyclopedia of Ocean Sciences*, J. Steele, S. Thorpe, K. Turekian (eds). Academic Press, London, UK. In the press.

The ocean surface is the interface between the two dominant, fluid components of the earth's climate system: the oceans and atmosphere. The heat moved around the planet by the oceans and atmosphere helps make much of the earth's surface habitable, and the interactions between the two, that take place through the interface, are important in shaping the climate system. The exchange between the ocean and atmosphere of heat, moisture and gases (such as CO_2) are determined, at least in part, by the sea surface temperature (SST). Unlike many other critical variables of the climate system, such as cloud cover, temperature is a well-defined physical variable that can be measured with relative ease. It can also be measured to useful accuracy by instruments on earth-observation satellites.
The major advantage of satellite remote sensing of SST is the high-resolution global coverage provided by a single sensor, or suite of sensors on similar satellites, that produces a consistent data set. By the use of on board calibration, the accuracy of the time series of measurements can be maintained over years, even decades, to provide data sets of relevance to research into the global climate system. The rapid processing of satellite data permits the use of the global-scale SST fields in applications where the immediacy of the data is of prime importance, such as weather forecasting, with the prediction of the intensification of tropical storms and hurricanes a particular example.

Minnett, P. J., R. O. Knuteson, F.A. Best, B.J. Osborne, J. A. Hanafin and O. B. Brown, 2001. The Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer. *Journal of Atmospheric and Oceanic Technology*,**18**, 994-1013.

The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) is described and some examples of the environmental variables that can be derived from its measurements, and the types of research that these can support are

briefly presented. The M-AERI is a robust, accurate, self-calibrating, sea-going Fourier-transform interferometric infrared spectroradiometer that is deployed on marine platforms to measure the emission spectra from the sea surface and marine atmosphere. The instrument works continuously under computer control and functions well under a very wide range of environmental conditions with a high rate of data return. Spectral measurements are made in the range of ~3 to ~18 μm wavelength, and are calibrated using two internal, NIST-traceable blackbody cavities. The environmental variables derived from the spectra include the surface skin temperature of the ocean, surface emissivity, near-surface air temperature and profiles of temperature and humidity through the lower troposphere. These measurements are sufficiently accurate both to validate satellite-derived surface temperature fields, and to study the physics of the skin layer.

Ward, B. and P. J. Minnett, 2001. An autonomous profiler for near surface temperature measurements. *Gas Transfer at Water Surfaces.* edited by M. A. Donelan, W.M. Drennan, E.S. Saltzmann and R. Wanninkhof. *American Geophysical Union Monograph.* Accepted.

This paper describes the profiling instrument SkinDeEP (Skin Depth Experimental Profiler), which measures the temperature of the water column from a depth of about 6 meters to the surface with high resolution thermometers. The instrument operates in an autonomous mode as it has the capability to change buoyancy by inflating a neoprene bladder attached to the body of the profiler. Measurements are recorded only during the ascending phase of the profile so as to minimize disturbances at the surface. Results from deployment of the profiler show strong temperature gradients within the bulk waters under conditions of high insolation. These data were compared to the skin temperatures as measured by the M-AERI, a high accuracy interferometric infrared spectroradiometer. The corresponding bulk-skin temperature differences (ΔT) were shown to have strong dependence on the depth of the bulk measurement during the daytime with low wind speeds, but at higher wind speeds, the depth dependence vanishes. One set of profiles under nighttime conditions is also presented, showing the presence of overturning and thus a heterogeneous temperature structure within the bulk.

F.2 Presentations:

Minnett, P.J., R. H. Evans and O.B. Brown. Prospects for Improved Sea-surface temperatures from MODIS – Superior Accuracy and Refined Applications. MODIS Science Team Meeting. Columbia MD, January 24-26, 2001.

Evans, R. H., P. J. Minnett, O.B. Brown, H.R. Gordon, K. Kilpatrick and E.Kearns. Results from NASA's Moderate Resolution Imaging Sprectroradiometer (MODIS): Global and Arabian Sea Regional Ocean Color and Thermal Observations. MODIS Science Team Meeting. Columbia MD, January 24-26, 2001.

Brown, O.B., P. J. Minnett, R.H. Evans and E.Kearns. Satellite Earth Remote Sensing: The Earth Observing System and the Next Decade. Oceanology International Americas 2001, Miami, FL, April 3-5 2001.

Minnett, P.J. Cloud masking for MODIS Ocean Color and Sea-Surface Temperature Retrievals. MODIS Cloud Mask Workshop, Madison WI, May 8 & 9, 2001.

Donlon, C.J., P.J. Minnett, I. J. Barton, T. J. Nightingale and C. Gentemann. Sea surface temperature measurements and definitions. Proceedings of the WCRP/SCOR Workshop on Intercomparison and Validation of Ocean-Atmosphere Flux Fields, Potomac, MD. May 21-24, 2001.